

Co-firing of imported wood pellets – An option to efficiently save CO₂ emissions in Europe?



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HIGHLIGHTS

- Co-firing has a low financial gap and allows for advantageous CO₂ mitigation costs compared to other renewable.
- Belgian and UK's co-firing subsidies are reasonable options to promote cost-effective renewable electricity generation.
- Co-firing subsidy schemes can effectively direct supply chain decisions towards low energy and carbon options.

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ABSTRACT

In this paper the energy and carbon footprints of pellet imports from Australia, West Canada, and Russia for co-firing in Europe are investigated. Their ecologic and economic performances are proven by applying the Belgian and UK co-firing subsidy systems, which require dedicated sustainability evaluations. Based on the modelling of different subsidy schemes and price scenarios, the present paper identifies favourable conditions for the use of biomass co-firing in Germany and Austria, which currently do not have dedicated co-firing incentives. The present paper shows that under present conditions, co-firing has a narrow financial gap to coal with −3 to 4 €/Cent/kWh_{el} and has low CO₂ mitigation costs compared to other renewables. Moreover, it is shown that co-firing is one of the most cost-attractive options to reach the EU-2020 targets. For policy makers, the support of co-firing is found to be very efficient in terms of cost-benefit ratio. It is proven that the co-firing subsidy schemes might direct supply chain decisions towards options with low energy and carbon impacts.

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1. Introduction

The European Union wants to strongly increase its share of renewable energy, whereby biomass plays a major role to fulfil the targets (EP, Council EU, 2009). There is a broad consensus among energy experts that the targeted share of bioenergy cannot be covered by domestically produced biomass only. Instead, for reaching the ambitious targets for 2020 and beyond, it seems inevitable that EU Member States will rely on biomass imports from non-EU countries, particularly for electricity generation, as reported by Hewitt (2011). Wood pellets are predestined for imports due to their high energy density. In fact, they are suitable for efficient transport over long distances. According to Lamers et al. (2012), EU imports of (industrial) pellets reached 2.5 mio t in 2010, which amounts to more than 20% of the EU consumption. Most imports are from Canada, with almost 1 mio t in 2010, from

the USA with 0.7 mio t, from Russia with 0.4 mio t and from Australia with 63,000 t. Junginger (2012) estimates that the EU pellet demand will rise to between 20 and 50 mio t by 2020. Considering a 'business-as-usual' scenario, he expects an increase of EU imports to almost 16 mio t in 2020, which is the sixfold amount compared to 2010. These pellet imports can have notable carbon and energy footprints, resulting from the production, pre-treatment, transport and logistics along the supply chain to Europe. So Hewitt (2011) states, that a consequence of satisfying the EU's 2020 objectives – a decrease of carbon emissions – could result in an actual increase of the EU's own carbon footprint.

The co-firing of biomass in coal conversion plants demonstrates one of the most straightforward and an easy-to-adopt technology for increasing the share of renewable electricity in Europe. Indeed, since several years, a couple of Member States like the Netherlands, Belgium, Scandinavian countries and the UK successfully applies this model by having effective co-firing subsidies (Cocchi et al., 2011; Al-Mansour and Zuwala, 2010). In 2010, the European Commission (EC) made recommendations for estimating and meeting sustainability criteria for solid biofuels (EC, 2010).

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These are already followed by many market actors and national authorities. As the public debate on sustainable solid biomass is persistent, the EC is expected to adopt a dedicated directive on the sustainability of solid biomass soon, which should be legal for all EU Member States.

In turn, the Member States are responsible to set the framework and incentives to promote the use of low-emission energy pathways. Up to now, no legally binding sustainability requirement exists for supporting the use of solid biomass in conversion plants, except from Belgium and the UK (EC, 2010; IPCC, 2012). In Belgium, the upstream energy or CO₂ balance of supplied biomass is assessed and included in the calculation of creditable co-firing subsidies (Van Stappen et al., 2007; Vlaamse Overheid, 2009). The UK wants to introduce binding sustainability criteria on the biomass upstream emissions in early 2013, which should be obligatory to receive support for co-firing (DECC, 2012a; OFGEM, 2011a). These subsidy models could be exemplary for other countries considering the support of biomass co-firing. For Central European countries like Germany, the co-firing of biomass in existing coal plants is already recognised as a very interesting and cost-effective option to reduce CO₂ emissions (DENA, 2011; Maciejewska et al., 2006).

When discussing the further increase of biomass use in Europe, a great controversy remains around the questions which kind of biomass can be seen as sustainable and how to effectively increase the share of electricity from renewables.

Thus in the present paper, the impact of co-firing imported wood pellets in Europe is assessed. In more detail, answers to the following questions are investigated:

- (1) Is co-firing of imported wood pellets efficient in terms of CO₂-eq savings?
- (2) What is the most sustainable biomass supply chain for import, regarding three real case studies (Australia, Canada, Russia)?
- (3) How do existing co-firing support schemes as in Belgium and the UK respond to the environmental footprint of concrete biomass imports? Which are the impacts on supply chain decisions?
- (4) Under which conditions is co-firing of imported biomass cost-effective for Germany and Austria?

This paper is organised as follows: Section 2 presents the methodological frame of the paper. The greenhouse gas and energy balances along the three supply cases from Australia, Canada, and Northwest Russia to the EU are provided in Section 3. In Section 4, a scenario analysis demonstrates, how the supply cases perform under the Belgian and the UK's co-firing support systems and which effects they have when applied to Germany and Austria. The findings are summarised in Section 5. Finally in the conclusion (Section 6), answers are given to the four central questions stated above.

2. Methodology and related work

2.1. Supply chain model

In this paper, three different case studies for long-distance pellet imports, i.e. from Australia, Canada and Russia, for co-firing in Europe are investigated for associated carbon footprints and under economic aspects. Studied phases include the energy input during raw material production, pellet production, transport to Europe, and delivery and conversion in coal based co-firing power plants. Fig. 1 represents the supply chain model, which is specifically investigated for Australia, Canada and Russia in Sections 3.1–3.3.

Because of increasing biomass resources and recent dominance over pellet imports into the European market, Western Australia, British Columbia (Canada) and Northwest Russia are chosen as the case studies (Lamers et al., 2012). These countries are expected to play an important role in future pellets imports to the EU (Deutmeyer et al., 2012; Junginger, 2012; Röder, 2010). The three selected chains with two raw material options allow a comparison of cases differing significantly in biomass source and distance, and thus give new insight into the environmental impact and the corresponding effects under co-firing subsidies.

Related work was accomplished by Hamelinck et al. (2005), who investigated a range of international bioenergy supply chains in terms of costs and energy balances. Uasuf (2010) studied a pellet chain analysis from Argentina to the Netherlands, and Maderthaner (2012) assessed the intra-European pellet trade. Similarly, the pellet export from British Columbia to the EU has been evaluated in terms of greenhouse gas (GHG) emissions by Magelli et al. (2009). Sikkema et al. (2010) investigated economics of the same system. These existing studies serve as a profound reference and for comparison of assessed supply chains in this paper (see Sections 3.1–3.4). The present study reassesses the Canadian case due to its prominent role in pellet exports to the EU and also for evaluating the new targets, as well as the effect on co-firing policy options. This paper includes the evaluation of the fossil fuel input, which has not been assessed before, and further considers different sourcing options. Comparable evaluations of the Australian and Northwest Russian pellet chains do not exist in literature and therefore are new in this paper.

Two different kinds of feedstock for each export country are considered, i.e. the “standard” one consisting of sawmill or wood residues, and an “alternative” one consisting of forest residues, plantation logs or roundwood. The latter one is used occasionally in the export countries in case of lack of standard feedstock or high competition with other sectors.

For the standard resources, two fuel options are distinguished for drying the raw material: biomass and natural gas. The most common fuel during pellet production is bark or other wood residues (Cocchi et al., 2011). Nevertheless, the option natural gas is considered in order to demonstrate the impact of increased fossil fuel use.

The pellet production phase is based on typical plant size capacity, on technology in use and on fuel specific energy consumptions which were based on the data by Obernberger and Thek (2010).

From the production site it is assumed that the pellets are transferred by train or truck to the export harbour of the respective country. From there, the pellets are shipped by bulk carrier (ocean) vessels to Western Europe. The inland delivery to the conversion plants is assumed to be by train. For Belgium and the UK similar logistics and prices are considered. Finally, the imported pellets are assumed to be co-fired in coal plants located in Belgium, UK, Germany, or Austria (see Section 2.3 for technological details).

Due to high ash contents caused by bark and other impurities, the considered pellets fulfil the EN-B category of ENplus classification (DEPI, 2011). Thus, the pellets are of sufficient quality for industrial use only.

All information and calculations are based on the net calorific value (NCV) of fuels. For pellets with 6% moisture content, the NCV is 4.9 MWh/t and for hard coal with < 2% moisture content, a NCV of 7.6 MWh/t was considered. The data specified in t (tons) are related to metric tons.

2.2. Environmental impact assessment

For assessing the environmental and sustainable impact of imported biofuels, the fossil and primary energy balance and

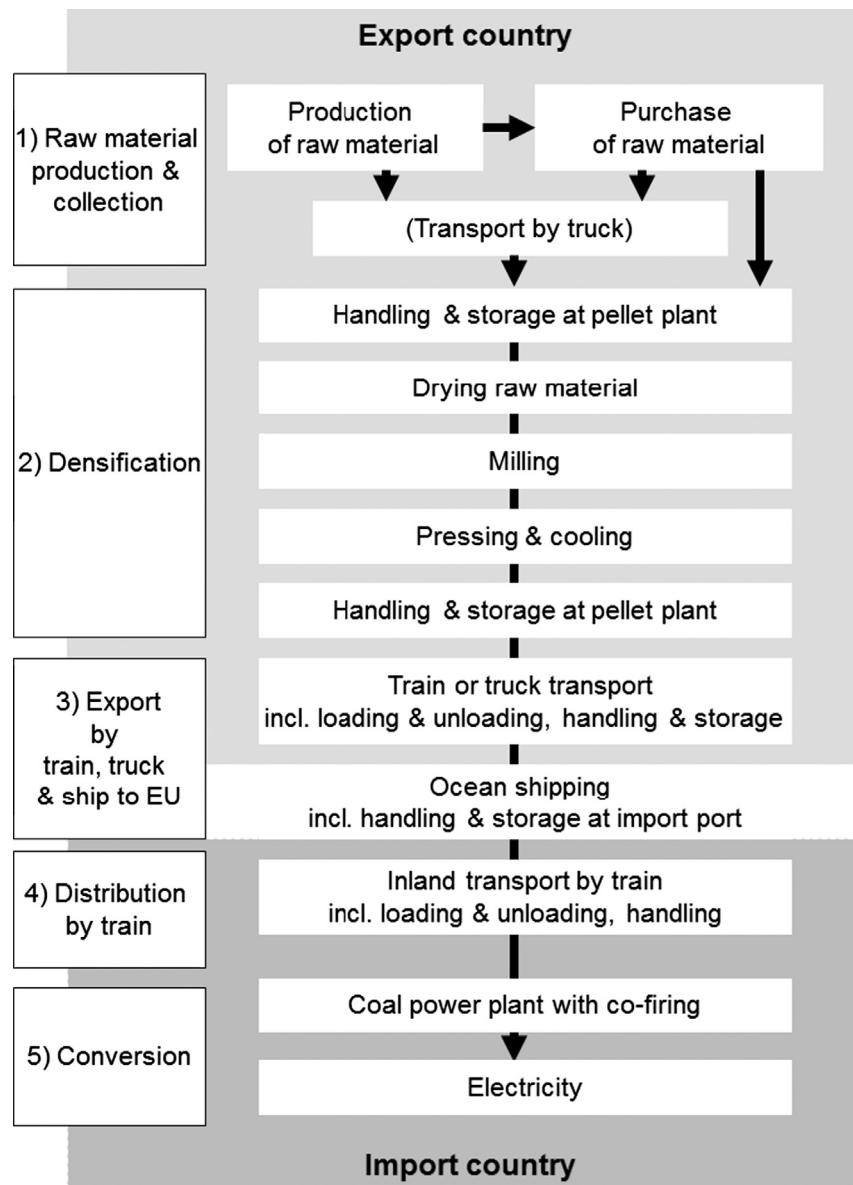


Fig. 1. Outline of pellet supply chain model.

CO₂-equivalent (GHG) emissions are modelled. The direct energy input from all supply chain processes is considered, which is derived from technology, logistic and process data. Respective mass balances and biofuel characteristics were taken from the biofuel database of TU Wien (2011). This approach is common and has been applied in numerous studies, e.g. Hamelinck et al. (2005), Uasuf (2010), Magelli et al. (2009) and Sikkema et al. (2010).

Conversion factors and the process efficiency in each supply step, the fuel and country specific emissions and the primary energy factors were extracted from the GHG databases Ecoinvent, accessed via software Gabi 4.4 (PE Int. and IKP, 2011), and GEMIS 4.7 (Ökoinstitut, 2011). For cross-border transports and logistics within the EU, the energy and emission factors for the EU's electricity or fuel mix are assumed. The greenhouse gases CO₂, CH₄, N₂O, perfluoromethan and perfluorethan (PE Int. and IKP, 2011; Ökoinstitut, 2011) are considered in the CO₂-eq calculations. Resources originating as a by-product from the wood processing industry or forestry were considered as CO₂-neutral up to the process of collection (EP, Council EU, 2009). For primary biomass resources the energy input during production of biomass was included. This assessment widely conforms to the recommendations by the EU

(EC, 2010). Potential land use and carbon stock changes are not considered in the present study.

The allocated CO₂ emissions from combustion are calculated according to the EU's emission trading system (EC, 2007), as described in Eq. (1).

$$CO_2 \text{ emissions} = E_{fuel} \cdot H_{u, fuel} \cdot EF \cdot OF \quad (1)$$

where CO₂ emissions is the annually emitted amount of CO₂, E_{fuel} is the fossil fuel consumed per year, $H_{u, fuel}$ is the net calorific value of the fossil fuel, EF is the emission factor, here: 353 kg CO₂-eq/MWh_{fuel} for hard coal, and OF is the oxidation factor, here: 1.

The emissions from biomass combustion are set 0, according to the Renewable Energy Directive of the EU (EP, Council EU, 2009). Thus, the following assessments suppose, that the removed carbon stock, dedicated for pellet production, regrows under approved forest (land) management practices (cp. Section 5 for further discussion).

The resulting energy inputs and GHG emissions are presented in kWh direct fossil or primary energy and kg CO₂-eq, each per ton of pellets. Taking the net efficiency of the conversion system into account, the energy input and emissions per MWh_{el} are derived.

Table 1

Key parameter for a new coal power plant with steam turbine.

Sources: BMU (2010), EC (2007), EEA (2011), ECN (2011), Maciejewska et al. (2006).

Average nominal capacity	800 MW _{el}
Basic investment	1040 mio €
Net efficiency	46%
Average operating hours	5000 h/a
CO _{2-eq} emissions for coal	768 g/kWh _{el}
Deprecation time	25 a
Interest rate	6%
Specific investment costs	1,300 €/kW
Operating costs	2% of investment costs/a
Additional investment costs for direct co-firing of wood pellets	300 €/kW _{el} for separate feeding and grinding unit for the preparation and co-firing of pellets
Additional operation costs during co-firing of wood pellets	3 €/kW _{el} due to increased pre-treatment efforts

The subsequent listing of energy consumptions and CO₂ effects in Sections 3.1–3.3 follows a structure similar to Sikkema et al. (2010).

2.3. Economic evaluation of pellets co-firing

A general evaluation and comparison of the UK's and German subsidy systems have been given by Mitchell et al. (2006). In the present paper, the subsidy schemes in Belgium and the UK are evaluated regarding the current and future financial support for co-firing. In Belgium and the UK, several large co-firing stations exist, which are fuelled by mainly imported biomass. Considering the different supply chain designs in this work, the support options for co-firing are compared and their application to Germany and Austria is investigated. For these countries, the electricity production costs, the financial gap of co-firing and CO₂ mitigation costs are modelled in different price scenarios, which are defined in Section 4.1.3. A comparison with current costs for other renewables proves the financial performance of co-firing. This type of policy evaluation is new and allows for new findings on effective strategies to reduce CO₂.

The economic evaluation is based on the co-firing of pellets in a 800 MW_{el} hard coal power plant. The technology and economic parameters are mainly derived from BMU (2010) and summarised in Table 1.

The annual capital costs are calculated according to Eqs. (2) and (3).

$$C_c = I_0 \cdot CRF \quad (2)$$

where C_c are the capital costs, I_0 the initial investment costs and CRF the capital recovery factor.

$$CRF = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \quad (3)$$

where i is the interest rate of the project, and n is the utilisation period of the equipment.

The electricity production costs (without heat extracts) are calculated according to Eq. (4).

$$C_{el} = \frac{C_c + OM}{E} + \frac{C_f}{\eta \cdot 0.0036} \quad (4)$$

where C_{el} are the levelised costs of electricity (per kWh), OM are the annual costs for operation, maintenance and other costs (in € per year), calculated as relative share (%) of investment costs, E is the annual electricity production, C_f are the annual fuel costs (in € per primary GJ) and η is the efficiency factor of the plant. The electricity production costs do not include VAT, revenues or supply charges.

Based on the electricity production costs of coal and those including 10% co-fired pellets, the respective financial gap can be assessed, as described in Eq. (5). The financial gap indicates the

difference in €-Cent/kWh_{el} of electricity production using co-fired pellets (10% pellets, 90% coal) and 100% coal. That means, a low financial gap induces higher profitability of co-firing, and electricity costs are closer to those from coal only. The more the financial gap turns negative, the higher is the cost advantage of electricity costs from co-firing against those from coal firing only.

$$FG = \frac{C_{co-firing} - (0.9 \cdot C_{coal})}{0.1} - C_{co-firing} \quad (5)$$

where FG is the financial gap, $C_{co-firing}$ are the electricity costs for 90% coal and 10% pellets firing, and C_{coal} are the electricity costs for coal only (each in €-Cent/kWh_{el}).

The CO₂ mitigation costs are indicated in €/t CO₂, which are incurred by the coal and co-firing electricity production costs and saved CO₂ emissions, see Eq. (6).

$$MC_{CO_2} = \frac{(C_{co-firing} - C_{coal}) \cdot 10 \cdot E_{output}}{CO_2 emissions} \quad (6)$$

where MC_{CO_2} are the mitigation costs (in €/t CO₂), E_{output} is the annual electricity output of the conversion plant (in MWh_{el}), and $CO_2 emissions$ are the annually emitted emissions (cp. Eq. (1)).

3. Emission and energy balances along pellet supply chains

3.1. Australian pellets to Europe

The South of Australia offers an increasing potential of eucalyptus (blue gum) plantations from marginal farm land destined for industrial pellets production (Smith, 2010; Röder, 2010). It is expected to supply a significant volume to the global pellet market, including Europe (Smith, 2010; Junginger, 2012). Forest plantation actors expect an extension of the plantation area from 0.58 mio ha in 2009 up to 2 mio ha in 2014. The industry announced an increasing set up of pellet plant facilities from current 250,000 t/a to 850,000 t/a production capacity in the near future (Waring, 2010; Smith, 2010). But different factors currently hinder the exports of pellets: The operator of the largest Australian pellet plant recently faced economic problems due to strength of Australian dollar to Euro and because of switching to more expensive raw material. Another factor influencing the Australian-European trade is the competition with Asia, which could lead to more exports from Australia to Japan or Korea (Waring, 2010). Also, Australia might request more pellets for its own demand. Thus pellet exports to the EU will be favoured only if 1) the production chain is optimised, 2) ocean freight rates are cheap, and 3) the exchange rate is favourable (Smith, 2010). Nevertheless, the EU is one of the dedicated target markets for pellet exports from Australia (Clean Energy Council, 2010; Electricity Forum, 2009; Lamers et al., 2012).

Table 2
Energy consumed and CO_{2-eq} emitted in the supply chain Australia – Europe.

	Basic data	Direct fossil energy input (kWh/t pellets delivered)	Primary energy input (primary kWh/t pellets delivered)	GHG emissions (kg CO _{2-eq} /t pellets delivered)	References
(1) Raw material production and collection					
Raw material transport	10 km to collection point	8.40	12.17	1.07	Own assumptions
Raw material preparation	Chipping plantation logs roadside, 45% mc, 5 l diesel/MWh biomass 3% mass losses	29.98	9.42	9.07	Suurs, 2002; Hamelinck et al., 2005
Raw material transport	50 km by truck (including empty return trip)	37.80	54.74	4.29	Assumption based on Smith, 2010; Waring, 2010
(2) Densification					
Handling & storage	0.25 kWh electricity and 0.02 l diesel/MWh biomass	1.89	4.78	1.55	Sikkema et al., 2010
Pellet production	120,000 t/a pellet production; 1% mass losses included				Adapted from Obernberger and Thek, 2010
Electricity consumption (for both process fuels)	26 kWh electricity/MWh pellets	125	474.39	158.71	
Natural gas consumption for drying	551 MJ/MWh pellets, 90% efficiency	760.68	874.72	192.512	
Biomass consumption for drying	551 MJ/MWh pellets, 90% efficiency	0.00	891.58	2.92	
Handling & storage	assumed as negligible				
(3) Export to Europe					
Transport to port Albany	40 km, truck	18.12	26.23	2.04	Waring, 2010
Handling & storage	0.25 kWh electricity; 0.02 l diesel/MWh biomass 1% mass losses	2.20	5.11	1.82	Sikkema et al., 2010
Ocean transport	40,000 t load capacity, 21,570 km, 0.0039 l heavy fuel oil/tkm 1,5% mass losses	959.41	990.34	285.00	Consumption from PE Int. and IKP, 2011; distance: AXS Marine, 2012
1)–3) Subtotal pellets delivered at Rotterdam harbour	Biomass (natural gas)	1183 (1943)	2469 (2452)	466 (656)	
(4) Delivery to conversion plant					
Handling & storage at import port	0.25 kWh electricity; 0.02 l diesel/MWh biomass	2.13	5.11	1.00	Sikkema et al., 2010
a) Transport to BE/UK	Train electric, 75 km	3.34	11.00	1.89	PE Int. and IKP, 2011
c) Transport to AT	Train electric, 1200 km	49.65	175.95	30.29	
Handling at coal plant	2.1 kWh electricity/MWh biomass	9.38	33.24	5.72	Sikkema et al., 2010
(5) Conversion in coal plant					
a) in BE/UK, pellets dried with biomass (natural gas)	800 MW _{el} coal plant, 46% electric efficiency	0.532 (0.872) MWh/MWh _{el}	3.291 MWh/MWh _{el}	212.55 (297.38) kg CO _{2-eq} /MWh _{el}	BMU, 2010
c) in AT, pellets dried with biomass (natural gas)		0.554 (0.895) MWh/MWh _{el}	3.37 MWh/MWh _{el}	225.25 (310.08) kg CO _{2-eq} /MWh _{el}	
For comparison: Conversion of hard coal in EU			4.49 MWh/MWh _{el}	900.55 kg CO _{2-eq} /MWh _{el}	

All primary energy and emission factors from PE Int. and IKP (2011), Ökoinstitut (2011).

The following analysis is based on the evaluation of an existing pellet plant in Western Australia replying on local eucalyptus plantations residues (Electricity Forum, 2009; Waring, 2010). The assumptions and results are listed in Table 2. The use of plantation logs is analysed as an alternative feedstock (see Table 3), which is a much more expensive but an actually used feedstock option for pellet production in Australia (SERCA, 2012; Grieve, 2012).

For the modelled supply case, a close distance between pellet plant and plantation area is assumed (Smith, 2010). The resulting CO₂ emissions from plantation to pellet plant gate are in agreement with those estimated for eucalyptus plantations in Thailand by Jawjit et al. (2006).

The modelled pellet production plant includes an additional grinding unit for coarse material (wood chips). The transport distance to the export harbour Albany is roughly 25 km by truck (Waring, 2010). The shipment to Rotterdam via the Cape of Good Hope accounts 21,570 km (AXS Marine, 2012).

3.2. Canadian pellets to Europe

British Columbia (Western Canada) has a vast potential of 417 mio ha forests representing the 3rd largest forest area in the world (Ferguson, 2010). An area of 60 mio ha is forested, with timber production on 25 mio ha woodlands. The lumber production was 27 mio m³ in 2010 (Bradley, 2010) with a resulting volume of sawmill residues (sawdust and shavings) between 18 and 25.6 mio m³/a (6.8 to 9.7 mio t_{dry}/a) (Verkerk, 2008; Wiik et al., 2009). The amount of biomass feedstock originating from forest harvest was around 9.95 mio t_{dry} in 2008 (Bradley, 2010). The resource base should be stable within the next years with an expected decrease from 2015 to 2017 induced by reduced cut of beetle infected wood (Wiik et al., 2009; Dahlberg, 2010).

The considered standard raw material for the pellet production is assumed to be sawdust and shavings from spruce (36% mc). The transport distance is 100 km to the pellet plant (Sikkema et al., 2010; Urbanowski, 2005).

The alternative raw material is wood chip residues from timber harvesting, (36% mc after air drying at roadside). The energy consumption for haulage and chipping of biomass (2.23 l diesel per MWh biomass) conforms to an average value for producing forest wood chips according to Riezinger (2008) and Suurs (2002). A supply radius of 150 km, which is the maximum feasible distance according to Verkerk (2008), is assumed.

Table 4 presents all supply steps for the standard case from Canada to Europe. The CO₂ emissions for ocean transport and the energy demand for drying raw material conform to the values assessed by Magelli et al. (2009).

Table 5 provides the results for the alternative feedstock including haulage and chipping at forest road. The use of forest chips implicates the need of an additional grinding unit in the pellet plant, resulting in slightly higher electricity input requirements.

3.3. Pellets from Northwest Russia to Europe

Russia is well known for vast wood reserves and a strong wood industry. The region Northwest Russia is favoured by direct access to the Baltic Sea. Saw mills in the Leningrad region surrounding St. Petersburg process more than 1 mio m³ wood per year (Karjalainen and Gerasimov, 2010). The annual forest waste composes at least 100 mio loose m³, reported by Cocchi et al. (2011). The number of pellet production plants is constantly growing. So, the 800,000 t/a production capacity in 2008 (Rakitova et al., 2009) and the recent increase by the 1 mio t/a pellet plant Vyborgskaya would amount to a total capacity of 1.8 mio t/a in the region. Up to now, the actual production is estimated at only 1 mio t/a (Rakitova, 2011). Most of the produced pellets are exported to the EU with comparably high revenue (Rakitova et al., 2009).

For the standard raw material case, sawdust from soft wood with a moisture content of 55% is considered. The supplying wood industry is nearby the pellet plant. As alternative feedstock, roundwood from regional coniferous forests is chosen. This is much more expensive than sawmill residues, and the use of primary wood resources is controversial (cp. Section 5 for discussion). Nevertheless, roundwood is used at the Vyborgskaya pellet plant (Cocchi et al., 2011; JSC Vyborgskaya Cellulose, 2012) and is therefore also investigated. For that case, tree harvesting is accounted with an energy consumption of 273 MJ/m³ (Magelli et al., 2009). The roundwood is transported 200 km to the pellet plant. A special roundwood handling and pre-treatment (debarking) unit is necessary. Similar technology used at Vyborgskaya plant (JSC Vyborgskaya Cellulose, 2012) is considered. This requires around 6 kWh electricity consumption per MWh_{biomass} and 0.34 l diesel per MWh_{biomass} for additional on-site transport efforts, according to Reisenbichler (2009).

A smaller pellet plant with 40,000 t/a capacity is taken into account, which is the case at the installed sites in Northwest

Table 3
Assumptions for alternative raw material plantation logs in the Australian pellets chain.

Basic data	Direct fossil energy input (kWh/t pellets delivered)	Primary energy input (primary kWh/t pellets delivered)	GHG emissions: kg CO ₂ -eq/t pellets delivered	References
(1) Raw material production and collection				
Alternative raw material: Eucalyptus plantation incl. energy use	43.02	13.38	13.01	Suurs, 2002; Ökoinstitut, 2011
wood chips from for production 5 l diesel/MWh biomass				
eucalyptus logs				
All other processing and operational phases 1)–3) are added as described in Table 2. For drying the use of biomass residues is assumed (same calculation as in Table 2).				
1)–3) Subtotal pellets delivered at Rotterdam harbour	1226	2483	480	
Operational phases for the delivery 4) are added as described in Table 2.				
(5) Conversion in coal plant				
a) in BE/UK, pellets dried with biomass	800 MW _{el} coal plant, 46% electric efficiency	0.555 MWh/MWh _{el}	3.303 MWh/MWh _{el}	BMU, 2010
c) in AT, pellets dried with biomass		0.577 MWh/MWh _{el}	3.382 MWh/MWh _{el}	
			218.37 kg CO ₂ -eq/MWh _{el} (upstream emissions)	
			231.07 kg CO ₂ -eq/MWh _{el} (upstream emissions)	

All primary energy and emission factors from PE Int. and IKP (2011), Ökoinstitut (2011).

Table 4Energy consumed and CO₂-eq emitted in the supply chain Canada – Europe.

	Basic data	Direct fossil energy input (kWh/t pellets delivered)	Primary energy input (primary kWh/t pellets)	GHG emissions: kg CO ₂ -eq/t pellets delivered	References
(1) Raw material production and collection					
Raw material at sawmill	sawdust & shavings from spruce, 36% mc	0	0	0	EP, Council EU, 2009
Raw material transport	100 km truck transport to saw mill 3% mass losses	66.66	96.52	7.57	Information from Sikkema, Faaij 2011
(2) Densification					
Handling & storage of raw material	0.25 kWh electricity and 0.02 l diesel/MWh biomass	1.77	3.94	0.69	Sikkema, Faaij 2011
Pellet production					
	120,000 t/a pellet production				Adapted from Obernberger and Thek, 2010; Urbanowski, 2005 and Magelli et al., 2009 for rotary drum dryer
	1% mass losses included				
Electricity consumption (for both process fuels)	22 kWh electricity/MWh pellets	70.93	259.29	35.42	
Natural gas for drying	299 MJ/MWh pellets, 90% boiler efficiency	418.72	483.62	103.72	
Biomass consumption for drying	299 MJ/MWh pellets, 90% boiler efficiency	0	522.16	0.74	
Handling & storage	assumed as negligible				
(3) Export to Europe					
Train transport to export port Vancouver	500 km, electricity	72.17	263.83	7.33	
Handling & storage	0.25 kWh electricity 0.02 l diesel/MWh biomass 1% mass losses	1.83	4.07	0.71	Sikkema and Faaij 2011; Suurs, 2002
Ocean transport by handymax vessel	40,000 t load capacity, 16,500 km, 0.0039 l heavy fuel oil/tkm 1.5% mass losses	722.93	749.99	215.83	Consumption from PE Int. and IKP, 2011; Distance: AXS Marine, 2012
Handling & storage at import port	0.25 kWh electricity 0.02 l diesel/MWh biomass	2.16	5.19	1.00	Sikkema, Faaij 2011; Suurs, 2002
1)–3) Subtotal pellets delivered at Rotterdam harbour	Biomass (natural gas)	936 (1355)	1900 (1861)	268 (371)	
(4) Delivery to conversion plant					
a) Train transport to conversion plant BE/UK	Train electric, 75 km	3.34	11.00	1.89	Consumption from PE Int. and IKP, 2011
c) Train transport to conversion plant AT	Train electric, 1200 km	49.65	175.95	30.29	
Handling at coal plant	2.1 kWh/MWh biomass	9.51	33.72	5.80	Sikkema et al., 2010
(5) Conversion in coal plant					
a) in BE/UK, pellets dried with biomass (natural gas)	800 MW _{el} coal plant, 46% electric efficiency	0.420 (0.604) MWh/MW _{el}	3.03 MWh/MW _{el} (incl. biomass)	122 (168) kg CO ₂ -eq/MW _{he}	BMU, 2010
c) in AT, pellets dried with biomass (natural gas)		0.441 (0.626) MWh/MW _{el}	3.108 MWh/MW _{el} (incl. biomass)	135 (180) kg CO ₂ -eq/MW _{he}	

All primary energy and emission factors from PE Int. and IKP (2011), Ökoinstitut (2011).

Russia (Cocchi et al., 2011). The overall supply chain patterns are listed in Tables 6 and 7.

3.4. Comparison of environmental impacts along the pellet chains

Based on the previous assessments (Sections 3.1–3.3), the direct energy consumption up to delivery at the conversion plant is shown for the three cases (Australia, Canada, Russia) in Fig. 2. Most direct fossil energy is used in the Australian case considering natural gas for drying (almost 2 MWh/t pellets), followed by the Russian and Canadian cases (natural gas) with a consumption between 1.6 and 1.4 MWh/t. All biomass cases are less extensive in fossil energy consumption, with the Russian biomass case at the minimum of only 0.3 MWh/t. Heavy fuel oil use during ocean transports has a strong impact in the Canadian and Australian cases. Production of plantation logs has a minor effect on the

overall balance for Australian pellets, but using roundwood doubles the fossil fuel input for Russian pellets compared to the standard case. The delivery of pellets either to Belgium or to Austria is similar as train transport is very energy-efficient.

Concerning primary energy, the difference between the use of natural gas and biomass is marginal only. Fig. 3 clearly demonstrates that due to the Russian electricity mix and drying of wet fuel, all Russian pellets cases have a higher primary energy consumption than Canadian pellets. Russian pellets from roundwood have an extremely high primary energy use due to raw material production and 60% increased energy input for pellet production. The results (2.51 MWh/t for pellets from Australia, 1.95 MWh/t from Canada and 2.05 MWh/t from Russia when biomass is used for drying) comply with the assessments by Sikkema et al. (2010), who reported 1.94 MWh/t for the Canadian chain to the Netherlands, and with Uasuf (2010) for Argentinian

Table 5

Assumptions for the alternative raw material forest residues in the Canadian pellets chain.

	Basic data	Direct fossil energy input (kWh/t pellets delivered)	Primary energy input (primary kWh/t pellets)	GHG emissions: kg CO _{2-eq} /t pellets delivered	References
(1) Raw material production and collection					
Alternative raw material: forest residues from coniferous wood	Haulage, air drying including chipping at roadside 2.23 l diesel/MWh biomass, 36% mc	34.20	130.15	33.09	Energy consumption from Riezinger, 2008; Suurs, 2002 Assumption based on Verkerk, 2008
Raw material transport	150 km truck transport to sawmill, 3% mass losses	99.98	144.78	11.36	
(2) Densification as described in Table 4 with exemption of electricity consumption:					
Electricity consumption	26 kWh electricity/MWh for wood chips	83.26	304.37	41.58	Adapted from Obernberger and Thek, 2010
(3) Export to EU import harbour as described in Table 4.					
1)– 3) Subtotal pellets delivered at Rotterdam harbour		1016	2299	315	
(4) Delivery to conversion plant as described in Table 4.					
(5) Conversion in coal plant					
a) in BE/UK, pellets dried with biomass	800 MW _{el} coal plant, 46% electric efficiency	0.455; MWh/MWh _{el} from pellets	3.206 MWh/MWh _{el} from pellets	142.60 kg/MWh _{el}	BMU, 2010
c) in AT, pellets dried with biomass		0.476 MWh/MWh _{el} from pellets	3.284 MWh/MWh _{el} from pellets	155.12 kg/MWh _{el}	

All primary energy and emission factors from PE Int. and IKP (2011), Ökoinstitut (2011).

pellets from sawdust (53% mc) with 1.79 MWh/t pellets, which are shipped 12,000 km to the Netherlands. Hamelinck et al. (2005) reported slightly lower values for pellets from Latin America to the Netherlands.

The greenhouse gas emissions along the supply chain are particularly high for cases with long ocean transports and natural gas use, as shown in Fig. 4. The resulting emissions are in agreement with Uasuf (2010) and Magelli et al. (2009).

Fig. 5 illustrates the GHG emissions of generated electricity from pellets imported from the three countries. The CO₂ savings related to the EU-average electricity mix are marked. All supply chains meet the 60% standard target of 285 kg CO₂-eq/MWh_{el}. Also the 66% savings (UK target for 2020) is achieved except for Australian pellets with process fuel natural gas.

4. Co-firing pellets from different sources under the Flemish and UK's support schemes

In this Section, the efficiency of co-firing under the influence of support schemes from Belgium and the UK is investigated. The Flemish and UK's subsidy systems as well as variable prices are outlined in Section 4.1. With these, different cases and scenarios for co-firing support are presented for Belgium, the UK, Germany and Austria (Section 4.2) and compared with other renewable energy generation in Section 4.3.

4.1. Policy and price assumptions

4.1.1. Green Certificate System in Flanders (Belgium)

In Belgium, co-firing biomass in coal plants is supported by the Green Certificate System (GCS). The GCS requires an inclusion of upstream biomass energy (i.e. direct fossil energy required to produce and transport the biofuel to the conversion plant). The number of credited green certificates for co-firing biomass in a coal plant is calculated according to Eq. (7) (Van Stappen et al.,

2007; Vlaamse Overheid, 2009).

$$GC = \frac{H_{u,pellets} \cdot \eta_{coal plant} - \sum E_{upstream,fossil}}{H_{u,pellets} \cdot \eta_{coal plant}} \cdot E_{pellets} \quad (7)$$

where GC is the number of annual Green Certificates granted for the co-firing of biomass in a coal plant (in %), $H_{u,pellets}$ is the net calorific value of pellets (in MWh), $\eta_{coal plant}$ is the electric efficiency of coal plant (in %), $\sum E_{upstream,fossil}$ is the total energy consumed during upstream production and transport operations (in MWh_{el}/t pellets), and $E_{pellets}$ is the amount of electricity produced from pellet co-firing (in MWh_{el}).

The value of one Green Certificate is at least 80 € per MWh_{el}, which corresponds to generation plants under operation prior to 2010 (EREC, 2009; Schachtschneider, 2012). This value is assumed for all considered scenarios.

4.1.2. Renewables Obligation Certificates (ROCs) in the UK

In the UK, the Renewables Obligation (RO) system provides support for the co-firing of biomass and energy crops (UK Secretary of State, 2009). For co-firing biomass, 0.5 Renewables Obligation Certificates (ROCs) per generated MWh_{el} are granted. For energy crops the support is 1 ROC/MWh_{el} (OFGEM, 2011b). The reference buy-out price for 2012/2013 is 40.71 £/ROC, which corresponds to 50.60 €/MWh_{el} (1 £=1.243 €).

Starting from 2011, the RO system requires biomass power generators to provide sustainability reports for the biomass feedstock. The target maximum level of GHG lifecycle emissions from resource to electricity generation is 285 kg CO₂-eq/MWh_{el} (cp. Fig. 5). From April 2013 onwards, meeting this GHG criterion should formally be linked with the eligibility for ROC support (OFGEM, 2011a; DECC, 2012a).

4.1.3. Fuel price scenarios

The Flemish and English subsidy schemes are analysed considering possible price variability for pellets, hard coal and CO₂ prices. Thus, three co-firing options are investigated under different price assumptions (cp. Table 8):

Table 6Energy consumed and CO₂-eq emitted in the supply chain Russia – Europe.

	Basic data	Direct fossil energy input (kWh/t pellets delivered)	Primary energy input (primary kWh/t pellets delivered)	GHG emissions: kg CO ₂ -eq/t pellets delivered	References
(1) Raw material production and collection					
Raw material from wood industry	residues from spruce, 55% mc	0	0	0	EP, Council EU, 2009
Raw material transport	truck transport 25 km on average, 3% mass losses	23.58	34.14	2.68	Information from Rakitova et al., 2009
(2) Densification					
Handling & storage	0.25 kWh electricity and 0.02 l diesel/MWh biomass	1.85	3.93	1.04	Sikkema et al., 2010
Pellet production					
40,000 t/a production, 1% mass losses					
Electricity consumption (for both natural gas and biomass as fuel)	23.1 kWh electricity/MWh pellets	105.99	321.49	84.17	Adapted from Obernberger and Thek, 2010
Natural gas consumption for drying	878 MJ/MWh pellets, 90% efficiency	1230.58	1353.64	308.68	
Biomass consumption for drying	878 MJ/MWh pellets, 90% efficiency	0	1312.00	1.10	
Handling & storage	assumed as negligible				
(3) Export to Western Europe					
Train transport to export port St. Petersburg	400 km, electricity	81.54	247.34	13.16	Distance from Karjalainen and Gerasimov, 2010
Handling & storage	0.25 kWh electricity; 0.02 l diesel/MWh biomass; 1% mass losses	2.17	4.59	1.21	Suurs, 2002; Sikkema et al., 2010
Sea transport	4000 t load capacity, 1600 km, 0.004 l heavy fuel oil/tkm, 1.5% mass losses	71.89	72.73	20.93	Direct consumption from Hamelinck et al., 2005
1–3) Subtotal pellets delivered at Rotterdam harbour	Biomass (natural gas)	287 (1518)	1996 (2038)	125 (433)	
(4) Delivery to conversion plant					
Handling & storage at import port	0.25 kWh electricity; 0.02 l diesel/MWh biomass	2.13	5.11	1.00	Suurs, 2002; Sikkema et al., 2010
a) Train transport to conversion plant BE/UK	Train electric, 75 km	3.34	11.00	1.89	Consumption from PE Int. and IKP, 2011
c) Train transport to conversion plant AT	Train electric, 1200 km	49.65	175.95	30.29	
Handling at coal plant	2.1 kWh/MWh biomass	9.38	33.24	5.72	Sikkema et al., 2010
(5) Conversion in coal plant					
a) in BE/UK, pellets dried with biomass (natural gas)	800 MW _{el} coal plant, 46% electric efficiency	0.133 (0.676) MWh/MWh _{el} from pellets	3.072 (3.091) MWh/MWh _{el} (incl. pellets)	58.66 (194.32) kg CO ₂ -eq/MWh _{el}	BMU, 2010
c) in AT, pellets dried with biomass (natural gas)		0.155 (0.698) MWh/MWh _{el} from pellets	3.15 (3.168) MWh/MWh _{el}	71.18 (206.84) kg CO ₂ -eq/MWh _{el}	

All primary energy and emission factors from PE Int. and IKP (2011), Ökoinstitut (2011).

- The base case and current policy case with actual market prices,
- Scenario 1 with low CO₂ and high pellet prices,
- Scenario 2 with moderate fuel and CO₂ prices,
- Scenario 3 with high coal and CO₂ prices.

For the base case, real market prices for industrial pellets and hard coal delivered to Rotterdam and CO₂ allowances are assumed. According to APX-ENDEX, the pellet market price in Rotterdam is assumed to be 130 €/t (APX-ENDEX, 2012). The prices for imported hard coal at the cross-border point is set 85 €/t for Belgium and the UK, and 90 €/t for Germany and Austria (EEX, 2012a; BAFA, 2012). The final fuel prices are listed in Table 8 and include inland transportation costs to the conversion plant, which are derived from Prognos (2006) and Sumetzberger (2012). The inland transport distance is assumed to be 75 km for Belgium and the UK, 400 km for Germany and 1200 km for Austria. The price for CO₂, auctioned at the European Energy Exchange, is set 15 €/t (EEX, 2012b).

Other incentives like tax reduction (BE) or market regulations (UK) are not considered. An outline of feed-in tariffs is given in Section 4.3.

4.2. Results of investigated co-firing options

4.2.1. Co-firing under current policies

In Fig. 6, the electricity production costs for coal combustion and co-firing of pellets are illustrated according to the current policy frame. As shown, the production costs with or without co-firing pellets do not differ substantially, but in most cases are still higher for co-firing. This particularly applies to Germany and Austria, where no co-firing support scheme exists. Here, the difference in production costs is around 0.40 to 0.45 €/Cent/kWh_{el} and the financial gap is between 3.64 €/Cent/kWh_{el} (Germany) and 4.06 €/Cent/kWh_{el} (Austria).

For comparison, the Belgium and UK's situations are included in Fig. 6. For Belgium, the electricity production costs for co-firing are much closer or even below those from coal only. The effect of offsetting the number of green certificates against the upstream energy balance results in a clear favouring of low energy biomass chains. In the UK, ROCs are constant for each case. Thus, the financial gap and CO₂ mitigation costs are equal for each case with forest biomass or with energy crops. Opposite to the Flemish system, in the UK the relatively energy intensive Australian chains

Table 7
Assumptions for alternative raw material roundwood in the Russian pellets chain.

Basic data		Direct fossil energy input (kWh/t pellets delivered)	Primary energy input (primary kWh/t pellets delivered)	GHG emissions: kg CO ₂ -eq/t pellets delivered	References
(1) Raw material production and collection					
Raw material production	Harvested roundwood coniferous, 55% mc Forest management, harvesting and haulage to forest road: 4.36 l diesel/MWh biomass 3% mass losses	183.14	205.11	55.38	Energy consumption from Magelli et al., 2009
Raw material transport	truck transport 100 km on average	92.41	133.81	10.50	Own assumption based on Rakitova et al., 2009
(2) Densification					
Handling & storage	0.25 kWh electricity and 0.02 l diesel/MWh biomass	1.82	3.85	1.04	Sikkema et al., 2010
Pellet production 40,000 t/a production 1% mass losses					
Roundwood pre-treatment	Electricity consumption including debarking 6.3 kWh/MWh biomass	23.85	72.33	18.94	Assumption based on Reisenbichler, 2009 and Eco World Styria, 1997
	On-site handling of roundwood 0.34 l diesel/MWh biomass	14.27	15.98	4.32	
Electricity consumption	27 kWh electricity/MWh pellets	124.43	377.43	84.172	Adapted from Obernberger and Thek, 2010
Biomass consumption for drying	878 MJ/MWh pellets (biomass residues), 90% efficiency	0	2152.50	26.78	
Handling & storage	assumed as negligible				
(3) Export to Western Europe see Table 6.					
1)–3) Subtotal pellets delivered at Rotterdam harbour		596	3286	251	
(4) Train delivery to conversion plant as in Table 6.					
(5) Conversion in coal plant					
a) in BE/UK, pellets dried with biomass	800 MW _{el} coal plant, 46% electric efficiency	0.269 MWh/MWh _{el} from pellets	3.641 MWh/MWh _{el} (including pellets)	114.56 kg CO ₂ -eq/MWh _{el}	BMU, 2010
c) in AT, pellets dried with biomass		0.291 MWh/MWh _{el} from pellets	3.72 MWh/MWh _{el}	127.09 kg CO ₂ -eq/MWh _{el}	

All primary energy and emission factors from PE Int. and IKP (2011), Ökoinstitut (2011).

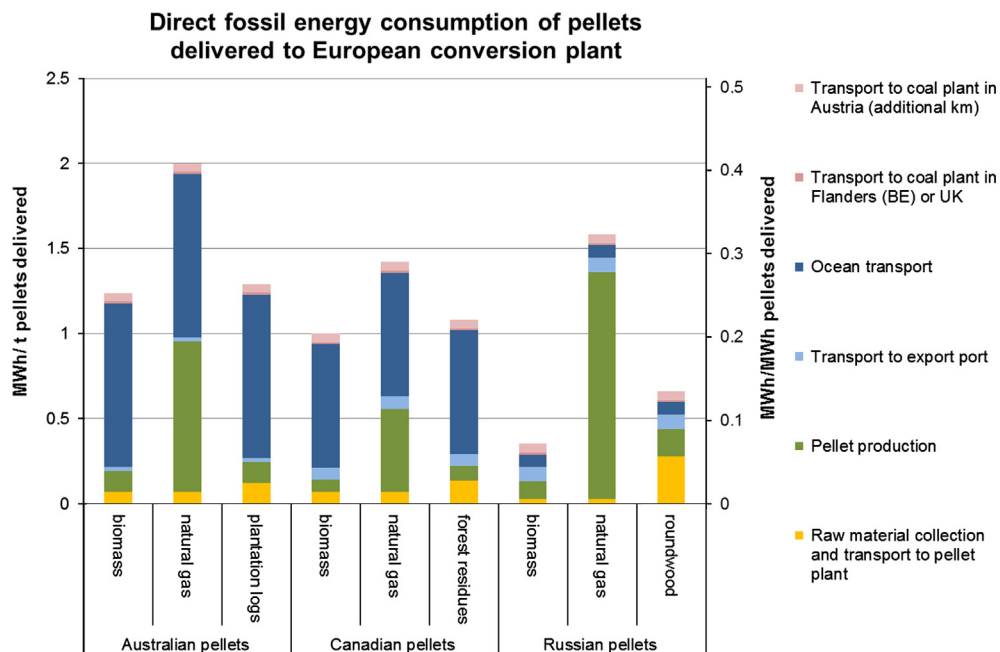


Fig. 2. Direct fossil energy consumption along the supply of exported pellets from Australia, Canada, and Russia to Europe. For electricity, the share of fossil energy included in the national electricity mix is considered. Handling, storage and loading activities are included in the preceding supply step.

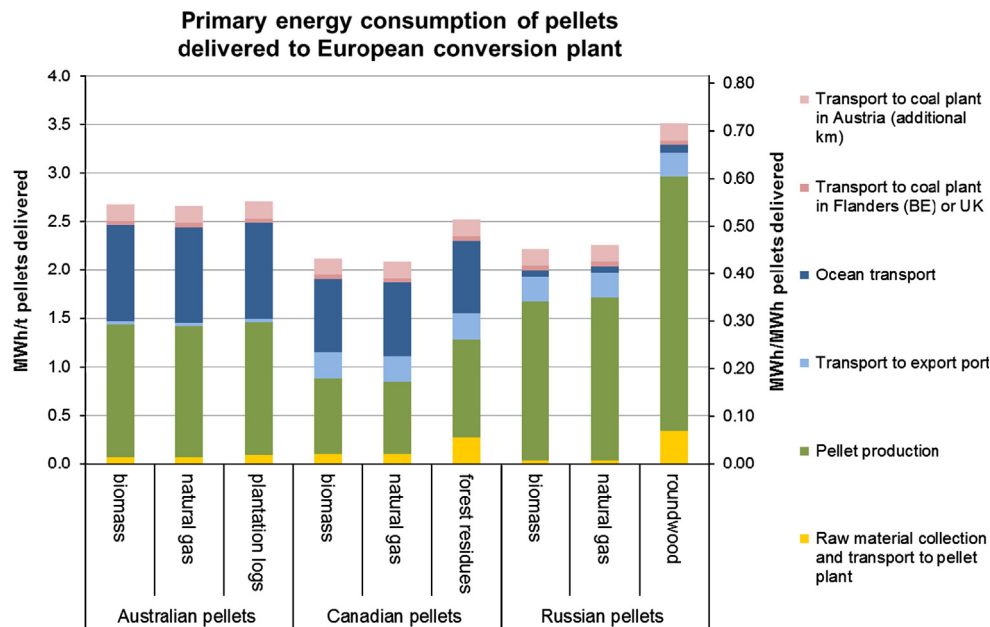


Fig. 3. Primary energy consumed along the supply chains of exported pellets from Australia, Canada, and Russia to Europe. Primary energy consumptions' calculation based on the direct energy consumption and the primary energy factor for the respective source of energy.

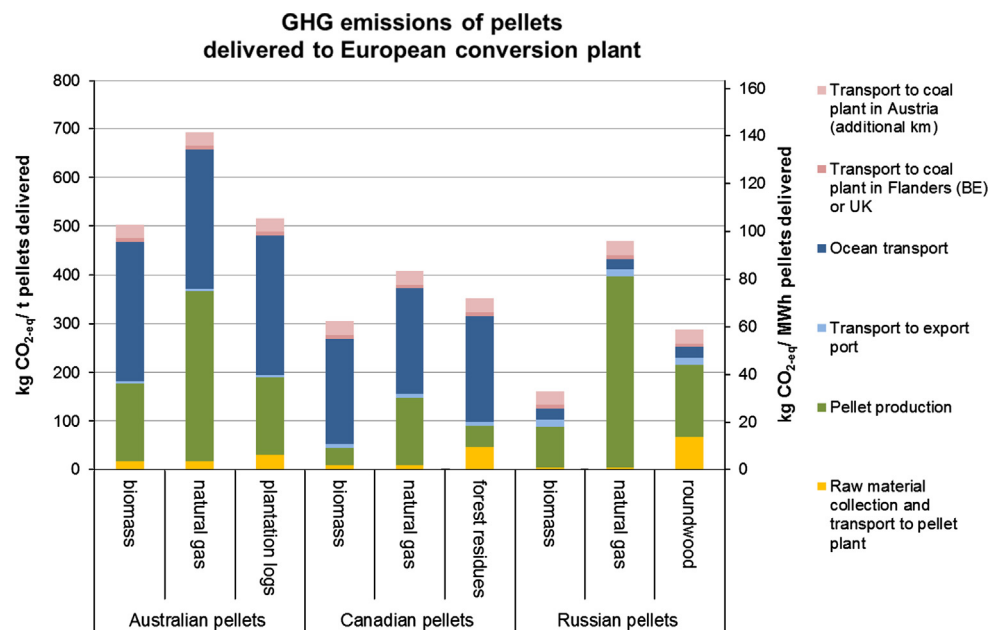


Fig. 4. Greenhouse gas emissions calculated along the supply chains of exported pellets from Australia, Canada, and Russia to Europe. GHG calculation based on the direct energy consumption and the GHG emission factor for the respective source of energy.

are credited with full certificates because energy crops are used. Co-firing Canadian and/or Russian pellets in the UK is still more expensive than electricity from coal.

4.2.2. Base case: Applying the Flemish and UK's co-firing subsidies to Germany and Austria

Here, the electricity production costs for co-firing pellets are adapted for Germany and Austria assuming that the Flemish or UK's co-firing subsidies are applied. Fig. 7 illustrates the situation with Belgium and the UK as comparative factors. The result is that cost levels approach those of Belgium and the UK with financial gaps mostly between 0 and 2 €/Cent/kWh_{el}.

4.2.3. Scenario analysis for variable fuel price development

Next, the co-firing support schemes are evaluated for different price scenarios (see Section 4.1.3, Table 8). Scenario 1 (Fig. 8) demonstrates low CO₂ and high pellet prices. The impact of unfavourable pellet price conditions becomes very obvious. Financial gaps are much higher, thus co-firing pellets becomes less attractive, especially for pellets dried with natural gas under the Flemish subsidy system. Australian pellets lose their cost advantage in the UK's system and reach a financial gap of 0.4 to 1.4 €/Cent/kWh_{el}. The Russian case (biomass) still achieves favourable values for Germany and Austria. The CO₂ mitigation costs mainly exceed the set market price for CO₂ with 7 €/t, except for the Russian cases with biomass as drying fuel and partially for Canadian pellets.

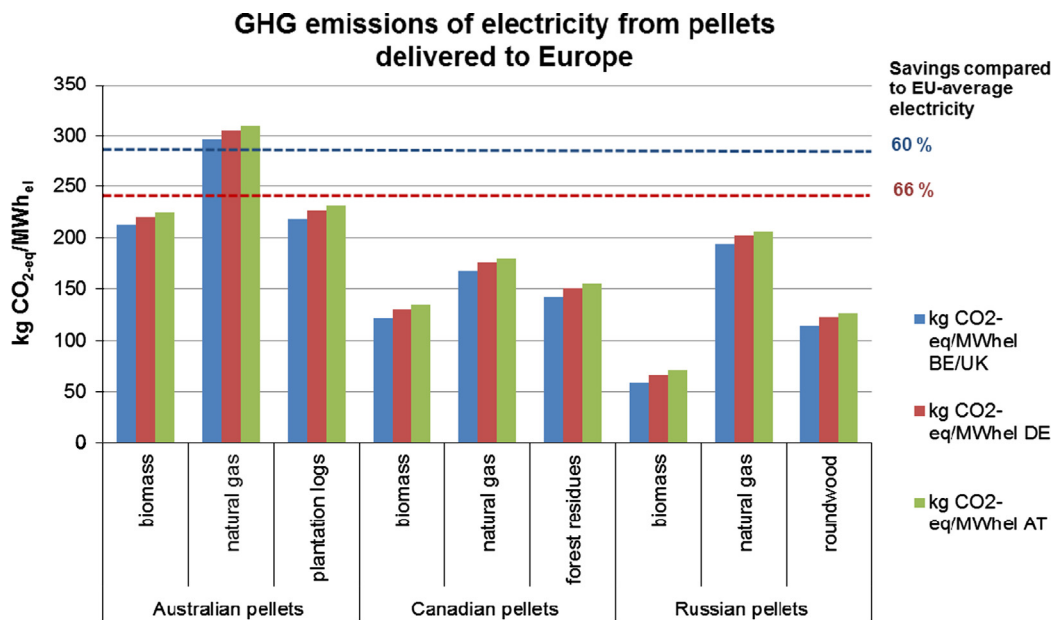


Fig. 5. GHG emissions per generated MWh_{el} from pellets exported from Australia, Canada, and Russia to the EU, and savings compared to EU average electricity mix. Source: Own results with UK's CO₂ saving targets from DECC (2012b).

Table 8

Base case and scenario price assumptions for fuels delivered at conversion plant and CO₂ allowances (in €).

Prices ex works	Pellets	Import hard coal	CO ₂ allowances
Base case und current policy case			
Belgium, UK	140.50	90.00	15
Germany	152.00	94.33	15
Austria	162.50	94.33	15
Scenario 1: low CO₂+high biomass costs			
compared to base case:	+20%	stable	Low
Belgium, UK	168.60	90.00	7
Germany	182.40	94.33	7
Austria	195.00	94.33	7
Scenario 2: moderate fuel and CO₂ prices			
compared to base case:	+10%	+25%	moderate
Belgium, UK	154.55	112.50	15
Germany	167.20	117.91	15
Austria	178.75	117.91	15
Scenario 3: high CO₂ and coal prices			
Compared to base case:	20%	40%	Peak 2005–2012
Belgium, UK	168.60	126.00	30
Germany	182.40	132.06	30
Austria	195.00	132.06	30

In scenario 2 (Fig. 9), moderate fuel and CO₂ prices are considered. Under this scenario, the production costs for co-fired Russian pellets (biomass) are very low under the Flemish support system, resulting in a financial gap of up to −2.95 €/Cent/kWh_{el}. Favourable CO₂ mitigation costs are also reached by Canadian pellets in Germany (biomass and forest residues). Australian pellets reach negative CO₂ mitigation costs under the RO system. The remaining cases have much lower CO₂ mitigation costs than in the base case, mostly between 0 and 30 €/t CO₂.

Scenario 3 (see Fig. 10) represents high coal and CO₂ prices. It shows that in the Flemish Green Certificate System pellets from all origin countries are favoured against coal, except for pellets with natural gas as process fuel. Once more, the UK's system represents an advantage for Australian pellets solely falling below coal costs.

For Germany, all pellets dried with biomass are cost-competitive under the Flemish system and have favourable CO₂

mitigation costs between −48 €/t and −4 €/t CO₂, under the English system between −24.4 and 8.5 €/t CO₂, and with −17 and 16 €/t CO₂ in Austria. All pellets dried with natural gas show a much lower financial gap with a maximum of 2 €/Cent/kWh_{el} under the Flemish system. In turn, the RO system results in financial gaps between −2 and 1 €/Cent/kWh_{el} with the most advantageous values for Australian “energy crop” pellets.

4.3. Comparison of co-firing with other expenditure on renewable electricity

Fig. 11 gives an outline of cost ranges for different renewable electricity (RE) technologies referenced by IPCC (2012). For comparison, the results from the base case in Section 4.2 (without funding) are included. With a cost range between 1.7 and 6.8 €/Cent/kWh_{el} (McGowin, 2008; own results), co-firing is one of the cheapest renewable energy technologies available. Only hydropower, onshore wind or geothermal energy can demonstrate cheaper alternatives when considering the minimum production costs, starting from 1.4 €/Cent/kWh_{el} (hydro), 2.9 (geothermal) and 3.4 €/Cent/kWh_{el} (onshore wind). In contrast, electricity from photovoltaic (PV) is the most expensive technology with costs between 13 and 53 €/Cent/kWh_{el}.

In terms of CO₂ mitigation, co-firing implicates costs between −43 and 59 €/t CO₂ (Fig. 12). Most other state-of-the-art renewables (compared to a reference electricity generation mix) are more expensive with 50 to 166 €/t CO₂ for biomass power (Kalt and Kranzl, 2011; E-Control, 2009), for wind power with 60–100 €/t CO₂ and for PV with 300–950 €/t CO₂ (DENA, 2011; E-Control, 2009). Only small hydropower in Austria (E-Control, 2009) and the current price for EU emissions (EEX, 2012b) allow for comparably low mitigation costs.

As evaluated in Section 4.2, the financial gap for co-firing (see Fig. 13) is between −3 €/Cent/kWh_{el} (Flanders) and 4 €/Cent/kWh_{el} (Austria). Compared with the current electricity support for renewables (BMU, 2012; OFGEM, 2012; Schachtschneider, 2012; OEMAG, 2012), the highest grants are spent on PV with 6 to 24 €/Cent in Germany, 8 to 26 €/Cent in the UK (supplementary to ROCs) and 50 €/Cent/kWh_{el} in Austria, 5 to 13 €/Cent/kWh_{el} for hydropower and 22 €/Cent/kWh_{el} for geothermal power in

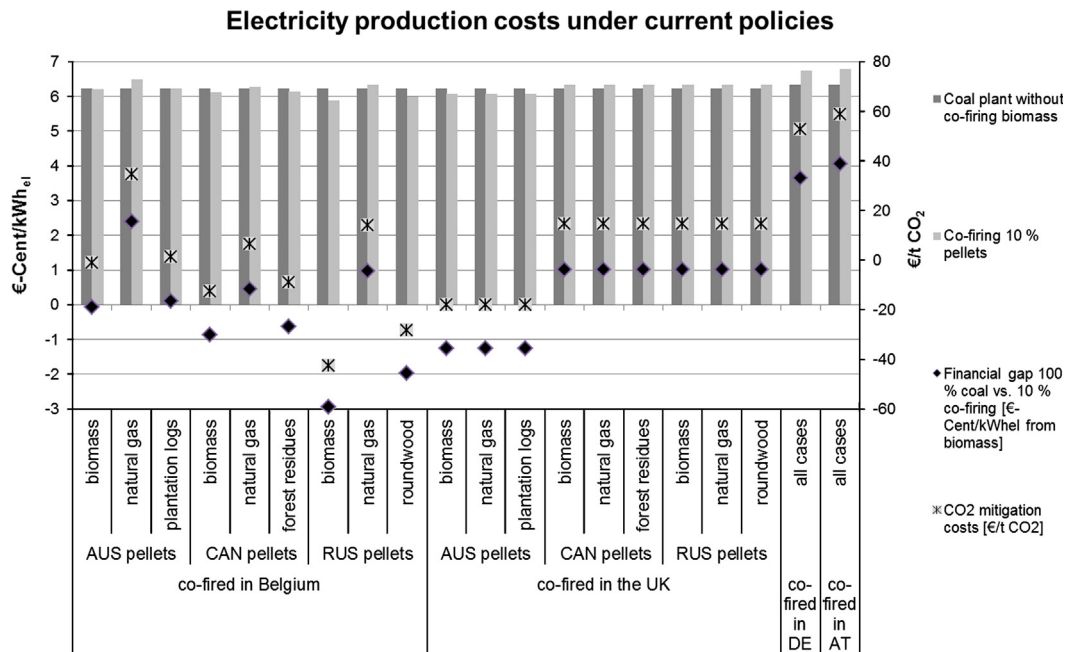


Fig. 6. Electricity production costs considering current national policies. Co-firing of 10% pellets in a 800 MW_{el} coal plant. Calculations include the CO₂ allocation according to EU regulations and the co-firing subsidies in Belgium and UK.

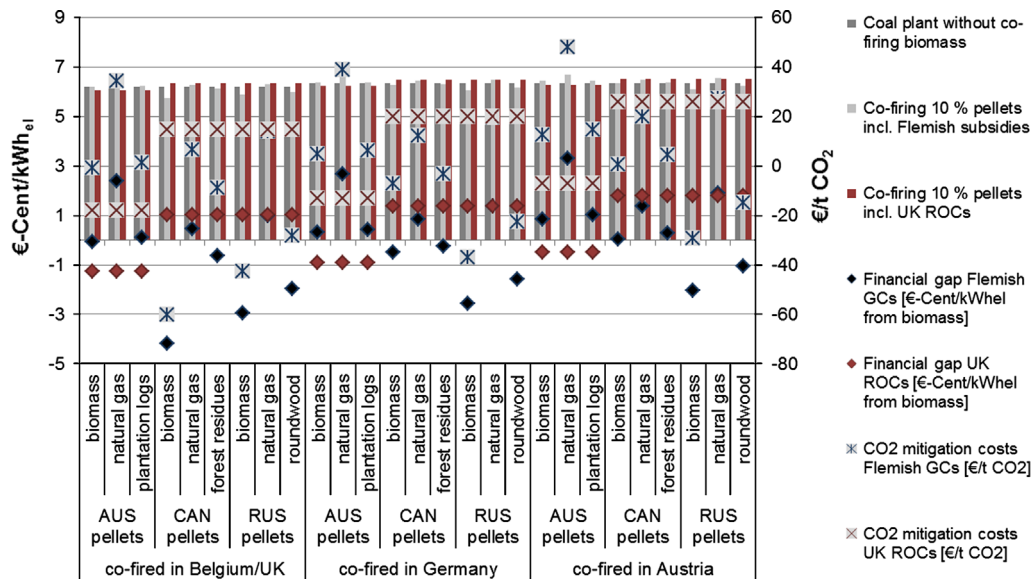


Fig. 7. Base case: Electricity production costs applying the Flemish and UK's co-firing subsidies to Germany and Austria.

Germany. When considering the relatively low biomass subsidies with 8 €/Cent/kWh_{el} in Belgium and 2.5 to 5 €/Cent/kWh_{el} plus 4 €/Cent for feed-in, co-firing biomass demonstrates a cost-attractive and low subsidised technology.

Therefore, the present study might serve as a supporting tool for policy makers in order to decide which sort of renewable energy technology should be promoted (via incentives or similar supports) from CO₂ emission reduction, economic constraints and sustainability point of view.

5. Summary and discussion of results

The present paper demonstrates, that energy balance and CO₂ emissions strongly depend on the individual supply chain design. This is clearly demonstrated by assessing the supply chains from

Australia, Canada, and Russia in Sections 3.1–3.3. When using renewable energy for the operations and choosing low emission transportation modes, imported pellets can have a very favourable energy and CO₂ footprint, even with long distance trading. Less favourable chains with high fossil fuel consumption can cause an upstream energy consumption up to half of the pellets energy content. The use of primary biomass like plantation logs has a minor effect on the fossil energy and GHG balance, but choosing roundwood for pellet production leads to doubled emissions (see Section 3.4).

When considering the co-firing support models in Flanders, it is demonstrated, that the German financial gap could be reduced from 3.6 (without funding) to between –2.6 and 2.7 €/Cent/kWh_{el}. For Austria, the financial gap could be reduced from 4.1 to between –2 and 3.3 €/Cent/kWh_{el}, with Russian (biomass) pellets the most advantageous. Under the English RO system, the financial gap

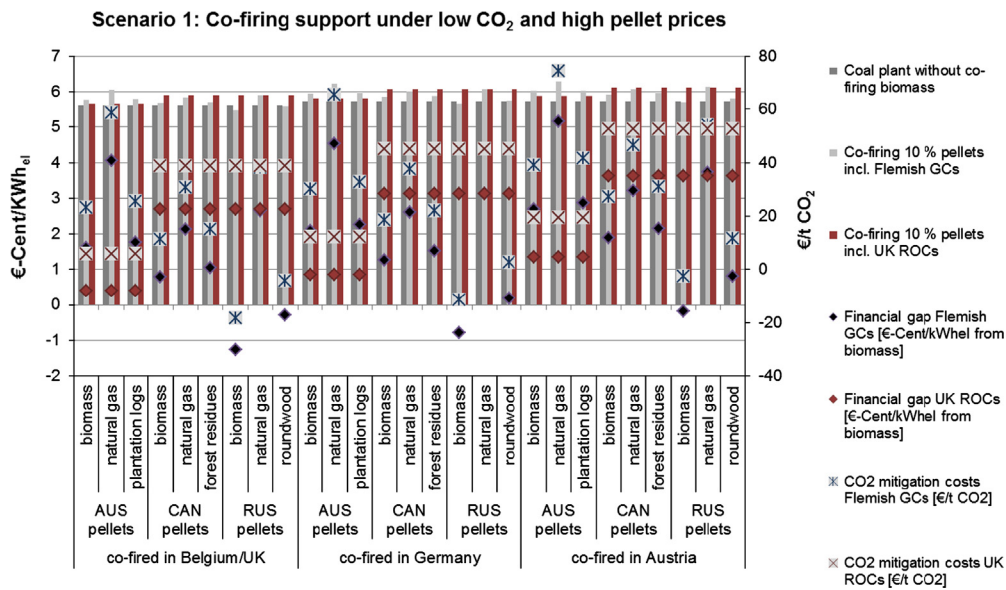


Fig. 8. Electricity production costs under scenario 1 (low CO₂ and high pellet prices).

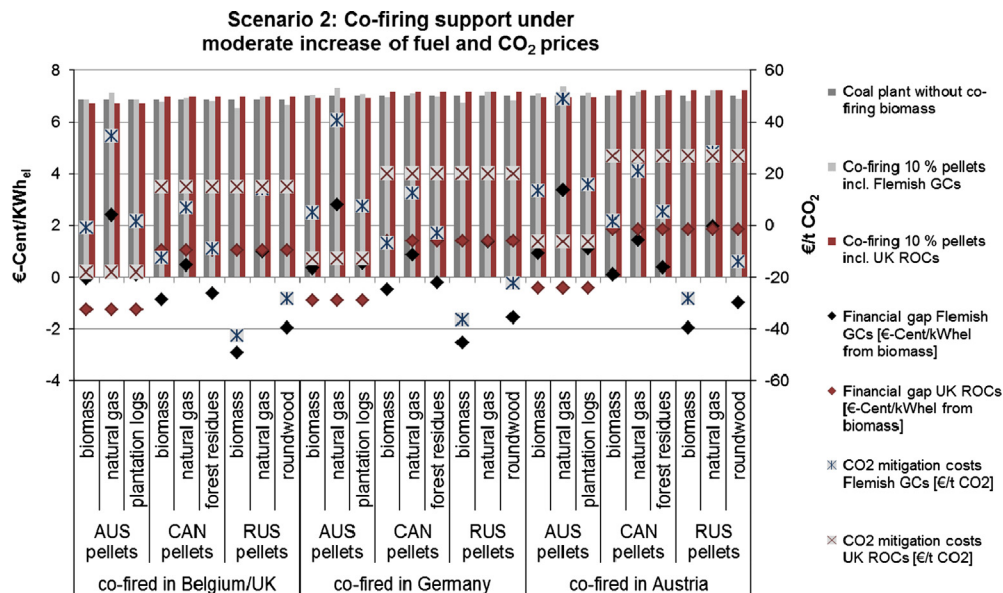


Fig. 9. Electricity production costs under scenario 2 (moderate fuel and CO₂ prices).

would be between -0.9 to 1.8 €/Cent/kWh_{el} in Austria and Germany. This system has a contrary effect when pellets are made of energy crops, which obtain the most advantageous revenues.

The main contributions of this paper are presented in Section 4.2. As a result, pellets transported from Australia to Europe and dried with natural gas are not profitable under the Flemish co-firing support. Under the UK's RO support, long distance is still financially viable when biomass is used for drying the pellets. It can be even more a cost-effective option when biomass comes from higher granted energy crops. This is already adopted in biomass power plants fed by overseas plantation wood like at Tilbury, UK (RWE, 2012). In turn, relatively low energy consuming chains like from Russia and those with high renewable energy input become more profitable when applying the Flemish subsidy scheme. Though, the supply from Russia has no advantage against longer distance supply with energy crops in the UK. The results show explicitly that the design of co-firing support effectively influences supply chain decisions. So, the available biomass sourcing options will be allocated to the best suitable support systems.

In Section 4.3, this work shows that, in comparison to different renewable production costs and subsidies as well as CO₂ mitigation costs, co-firing is a cost-effective option to produce renewable electricity even without or relatively low incentives. Thus, co-firing is one of the cost-attractive solutions to reach the EU 2020 targets and can be even attractive for countries with no or less co-firing support.

Finally, it should be noted that the current EU emission accounting does not consider changes in the carbon stock or (in) direct land use during biomass production, which is a general weakness of the existing system. Comprising these effects, researchers like Zanchi et al. (2010) found that, in the long run, specific biomass feedstock can effect even higher greenhouse gas emissions than coal, e.g. when dedicated tree fellings occur or land is converted for bioenergy purposes. Also, the combustion of biomass is only CO₂-neutral, if the same amount of biomass regrows in the same period on global scale.

In this regard, sourcing options as well as the present EU emission accounting system have to be treated carefully. However, Zanchi et al. (2010) did not consider positive effects from fellings

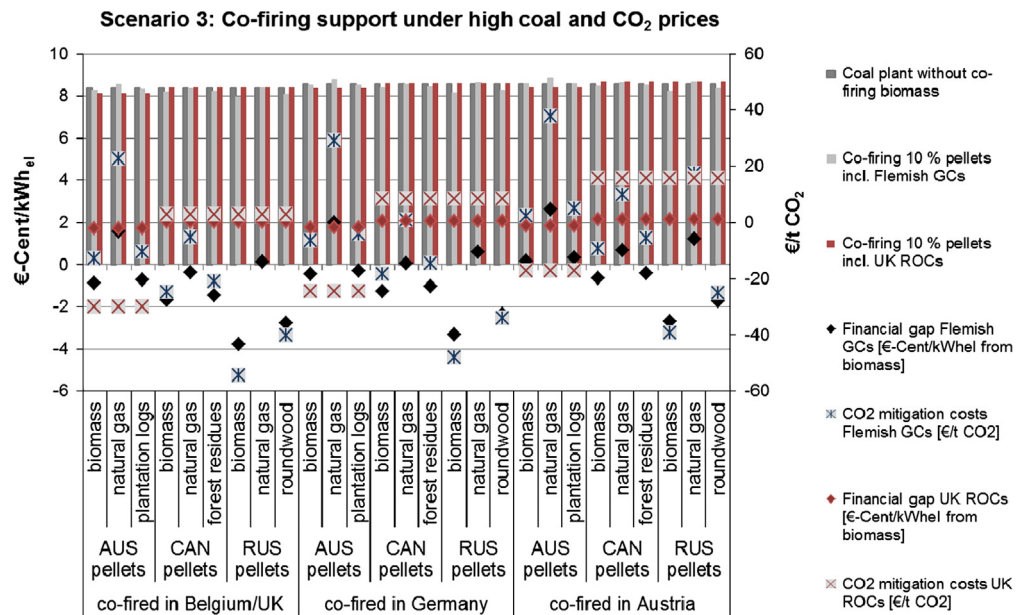


Fig. 10. Electricity production costs under scenario 3 (high coal and CO₂ prices).

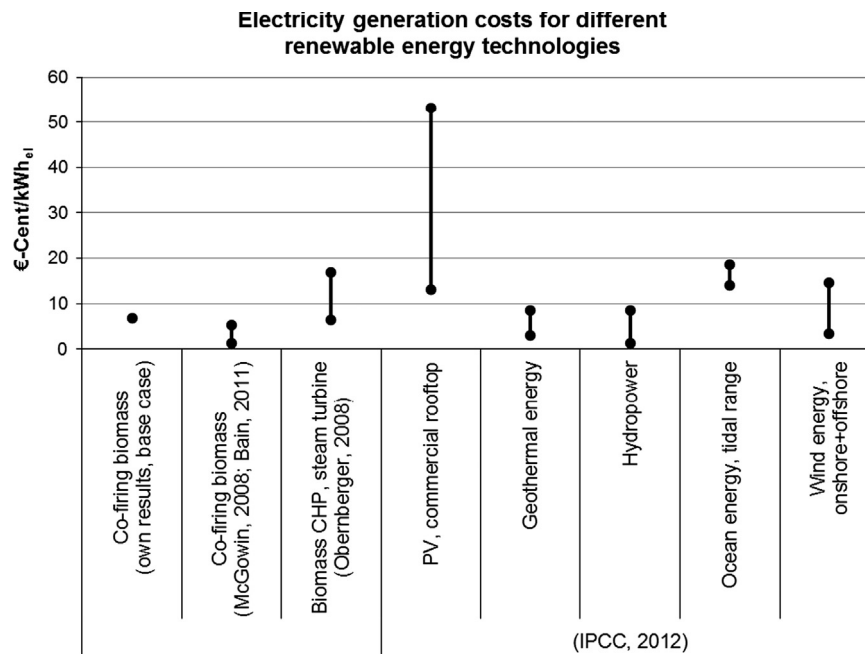


Fig. 11. Levelised costs of electricity generation for different renewable energy technologies.
Sources: own results, McGowin, 2008; Bain, 2011; Oberberger et al., 2008; IPCC, 2012.

or good land management practices. A comprehensive evidence of carbon balances for wood production can be found in publications by EEA (2011), Mitchell et al. (2012) and Nabuurs et al. (2008). One approach might be to give priority to energy production from biomass residues (as analysed under the “standard” biomass cases in Sections 3.1–3.4), except if those are needed to sustain soil fertility. Also, acknowledged certification systems as accredited by the Forest Stewardship Council require forest management practices, which should maintain or restore carbon stocks. Being aware of the need for certification, electric utilities are already used to purchase certified biomass, which should origin from integrative forest management practices. However, a desirable future approach should end up in a common accounting and certification policy, which considers these aspects thoroughly.

6. Conclusions

Based on the results of the previous sections, answers are presented to the four central questions raised in the introduction. As well, need for further research work is discussed.

6.1. Co-firing imported pellets – An option to efficiently save CO₂ emissions in Europe?

6.1.1. Is co-firing of imported wood pellets efficient in terms of CO₂-eq savings?

Imported and co-fired pellets are an attractive fuel for producing cost-effective renewable electricity and mitigating CO₂ emissions even when sourced over long distances. They offer an

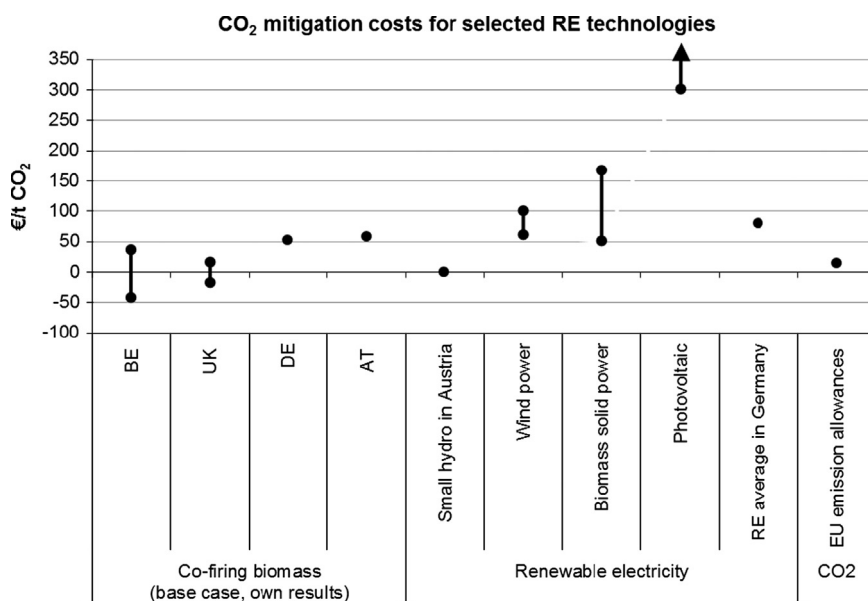


Fig. 12. CO₂ mitigation costs for co-firing biomass (reference coal plant) and selected renewable energy technologies for power generation (compared to natural gas or respective expenditure on support payments).

Sources: own results; Schwarz et al., 2011; Kalt and Kranzl, 2011; E-Control, 2009; DENA, 2011; EEX, 2012b.

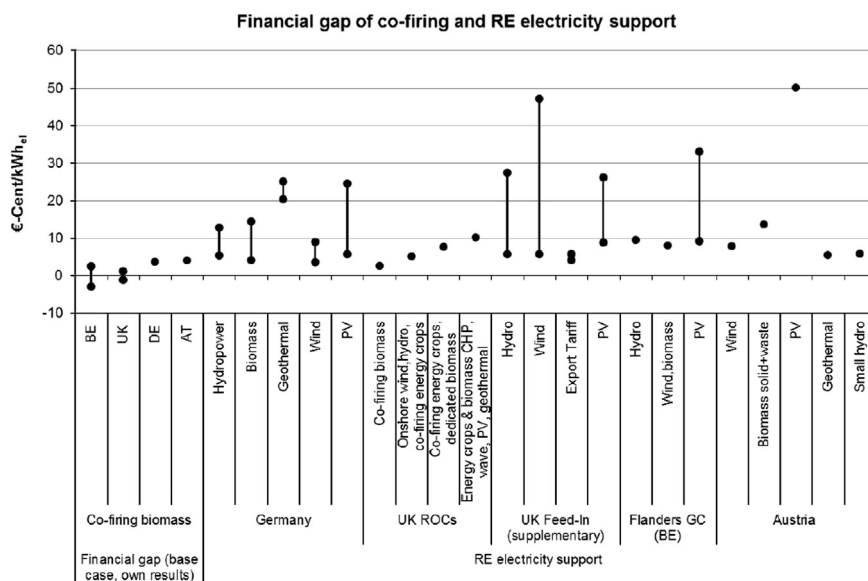


Fig. 13. Financial gap of electricity costs from co-fired pellets against coal firing only (base case) and reference subsidies for electricity generation from renewable energy in Germany, UK, Flanders (BE) and Austria.

Sources: own results; BMU, 2012; OFGEM, 2011b; Schachtschneider, 2012; OEMAG, 2012.

effective opportunity to quickly raise the share of renewables in the EU energy system. Nevertheless, in terms of effective sustainability, the assessment for biomass should follow a more integrated approach, as indicated in Section 5, taking into account aspects like carbon stock change and good land management practices.

6.1.2. What is the most sustainable biomass supply chain for import, regarding three real case studies (Australia, Canada, Russia)?

The assessment of the three supply chains has shown that a sustainable supply chain is characterised by a high share of renewable energy, high efficiencies and reduced carbon intensive fuels (using biomass for drying, train or vessel transportation in

large volumes instead of truck, electricity generation mix). The distance itself is not a crucial factor.

6.1.3. How do existing co-firing support schemes as in Belgium and the UK respond to the environmental footprint of concrete biomass imports? Which are the impacts on supply chain decisions?

This paper shows that the co-firing subsidy systems in Belgium and the UK have a high significance when only supporting the less energy or carbon intensive supply chains. They could set the direction towards subsidy schemes for imported biomass in other countries like Austria and Germany, and not for industrial use only. Besides, the requirements of subsidies have a relevant effect on the actual sourcing options allocated to the countries. In this way, even

import chains with higher emissions can be favoured in the UK when energy crops are used. In turn, the Flemish system has no biomass preference and grants most green certificates to the lowest fossil upstream energy use.

Considering the large amounts of co-fired biomass in Belgium, this market instrument turns out to be effective. For electric utilities, choosing supply regions in closer proximity could be an approach for getting higher grants. This system is somehow consequent in terms of reducing the use of fossil fuels, but for the destination, Belgium delimits the utilisation of pellets offered on the market. First of all, the choice of the supply chain will highly depend on where, how much and at which costs biomass is actually available (see Ehrig et al., 2011; Röder, 2010). Also, the assessments show that biomass sourced from intra-continental trade is not necessarily the best economic choice. It can even be uneconomic under the co-firing support schemes, e.g. when transported by truck. Furthermore, biomass support schemes should be reconsidered carefully regarding the use of primary biomass such as roundwood or biomass from plantations.

6.1.4. Under which requirements is the co-firing of imported biomass a cost-attractive option for Germany and Austria?

Co-firing in Germany and Austria is a competitive option considering the much lower production and CO₂ mitigation costs compared with other renewables. With a financial gap of 3.6 to 4.1 €/Cent/kWh_{el}, co-firing is still more expensive than in countries with dedicated support. When aiming at a significant and low cost solution for increasing the share of renewable electricity, co-firing is a very good option for policy makers as well as electricity generators for fulfilling their renewable energy targets even without financial support. Policy can effectively foster the process and attract sustainable import chains by introducing subsidy schemes as in the UK or in Belgium. Another influencing factor for co-firing are the coal and CO₂ allowance prices, which are still too low for making pellets a directly competitive fuel. But in turn, imported biomass can become cost-competitive against regionally sourced biomass, especially when the latter is getting scarce (Hermes, 2012).

6.2. Need for further research

Need for further research can be stated concerning the co-firing of torrefied pellets (Dusan, 2011; Maciejewska et al., 2006). Important decision factors for their use are the production in commercial volumes and a competitive market price, which can be proven when commercial production starts. With increased energy density of the fuel, the energy and CO₂ balances could be improved and therefore mean a better performance in receiving co-firing support or considering new sourcing options.

Further research is required on comprehensive emission accounting and certification systems for (forest) land management practises. These systems should take into account carbon stock balances, land use changes, as well as quantitative and qualitative aspects for land management.

Besides the considered chains, there are a lot of other promising biomass producing countries (e.g. Latin America), which should be considered in order to satisfy the growing demand of biofuels. The present paper shows that even biomass options from the other side of the globe can be economically and ecologically competitive to alternatives from closer origins.

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